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Impact and Residual Fatigue Behavior of ARALL and AS6/5245 Composite Materials

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I. INTRODUCTION

The current effort to make aircraft structures lighter in order to improve operational efficiency and performance has primarily resulted in the greater use of resin matrix composites. The current generation of composites offers many outstanding characteristics, however, there are some problems. Composites are susceptible to impact damage that is very hard to detect visually. Also, composite fabrication may requires a large capital expenditure by the aircraft manufacturer to convert from current metals technology.

Previous research [1-5] has demonstrated that a laminate comprised of thin sheets of aluminum adhesively bonded together offers significantly improved fracture toughness and damage tolerance over monolithic material of the same thickness. These laminates can therefore be used to save structural weight [6 and 7]. The higher toughness is attributed to the individual plies failing in plane stress, instead of plane strain as a monolith of the same plate thickness would [1]. The improved damage tolerance is attributed to four factors: (a) higher fracture toughness of the thinner materials, (b) slower crack growth rates in thinner materials, (c) lower stress-intensity factors in a cracked ply due to load transfer to an uncracked ply, and (d) the crack in one ply cannot easily grow past the adhesive into an adjacent uncracked ply [3,5]. This latter factor gives the material a "fail-safe" characteristic. Similar advantages for laminated titanium was shown by the author in reference [8].

In the early 1980's, researchers at Delft University of Technology, The Netherlands, carried the laminated metals concept one step further by introducing the Aramide Reinforced Aluminum Laminate (ARALL) [9]. This laminated concept incorporates unidirectional aramide fibers in the adhesive layer as illustrated in Figure 1. This arrangement allows the ARALL material to be prestrained, resulting in the aluminum sheet having residual compressive stresses as explained in reference [9]. The prestrained ARALL has outstanding fatigue and crack growth resistance properties as shown in Figures 2 and 3, respectively [10].

The purpose of the current research was to determine the impact damage resistance of the ARALL material and compare it to that for monolithic aluminum alloys and for a state-of-the-art composite system. Impacted specimens were also fatigue tested to determine residual fatigue strength.

II. SPECIMENS

Two types of specimens were fabricated and tested: (1) 76 mm by 102 mm plate for static indentation tests, and (2) 76 mm by 406 mm plate for impact and residual fatigue strength tests. Static indentation tests were conducted on five different materials: 2024-T3 aluminum, 7075-T6 aluminum, ARALL 7075 aluminum prestrained, ARALL 2024 aluminum not prestrained, and AS6/5245 composite. Residual fatigue strength tests were conducted on only the two ARALL materials and the composite. The thicknesses and moduli of the materials are shown in Table 1. Notice that the $[0_2/45/-45/90]_s$ composite layup and the ARALL materials have almost the same thickness and longitudinal modulus. All the tested materials are considered to be thin enough to exhibit membrane behavior. Therefore, although the thicknesses are not identical, the results will be compared without accounting for the difference in thickness. For much thicker plates of these materials the ranking of impact behavior could be different. The composite material was found to be approximately 25 percent lighter per volume than the ARALL.

Each ARALL laminate was comprised of three layers of 0.30 mm thick aluminum separated by 0.22 mm thick layers of continuous unidirectional aramid fibers in an epoxy matrix. The aramide fibers were oriented in the same direction between each aluminum layer.

The ARALL* material was supplied by the Aluminum Company of America (ALCOA), Pittsburgh, PA, while the AS6/5245* prepreg was purchased from Narmco Materials Incorporated, Anaheim, CA. The AS6/5254 material was chosen as a good state-of-the-art composite because of its performance in a recent comparison test [11].

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* The use of trade names in this paper does not constitute endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

III. EXPERIMENTAL PROCEDURES

The purpose of the experimental program was to answer two basic questions concerning impact:

(1) For each material studied, how much energy is required to produce

(a) visual evidence of impact?

(b) first damage (cracking)?

(c) front and backface damage?

(2) Given the same dynamic impact level, what are the residual fatigue strengths of the ARALL and composite material?

The first question was answered by a series of static indentation tests [12]. Based upon these results, the dynamic impact level was chosen for the residual fatigue strength tests.

The visual evidence of impact was defined as a dent on the surface that could be seen with the naked eye. First damage was defined as cracking somewhere within the specimen and did not include permanent plastic deformation alone. The front and backface damage is defined as visible damage (cracking) on both the front and back faces of the specimen in the test area.

A. Static Indentation Tests

The static indentation tests were similar to those performed by Bostaph and Elber [12]. They showed that static indentation tests were equivalent to dynamic impact if the material studied was sufficiently thin. This static load testing was conducted in a servo-hydraulic testing machine. Essentially, the loads and displacements were measured and recorded as a punch was pushed into the plate material of interest. The punch consisted of one-half of a 25.4 mm diameter steel ball bearing mounted on the end of a rod. The test plate was constrained between two 25.4 mm thick steel plates containing circular cut-outs 50.8 mm in diameter. The steel plates were tightly bolted together to hold the test plate securely in place. Care was taken to insure that the center of the test plate coincided with the center of the hole in the steel plates. Figure 4 is a schematic of the test set-up.

The load versus displacement was recorded on an X-Y plotter and the area under the curve was measured using a planimeter. The area (in terms of N-m) is equal to the energy put into the material.

The indentor was displacement controlled. This allowed for the unstable portion of the load/displacement curve to be recorded and individual damage events to be easily identified. When damage events were observed on the load/displacement plot as a sudden drop in load, the test was sometimes stopped and the specimen removed in order to define the damage. The specimen would then be replaced in the test fixture and the test resumed.

B. Dynamic Impact Tests

The dynamic impact tests were conducted using a drop weight tower. The test plate was placed between the steel plates as in the static indentation tests. The same 25.4 mm diameter steel ball was used. The ball was attached to a drop weight such that the total weight of the unit was 15.8 N. The unit was then dropped from the appropriate height to give a specified impact energy level. The unit was caught after the first impact to prevent subsequent impacts due to rebounding.

C. Fatigue and Residual Strength Tests

After the specimens were dynamically impacted, they were fatigue tested for two million cycles at a cyclic stress range of 207 MPa and a stress ratio of 0.1. A servo-hydraulic testing machine was used at a test frequency of 10 cycles per second.

If the specimen failed before two million cycles, the number of cycles to failure was recorded. If the specimen did survive two million cycles, the load was quasistatically increased until complete specimen failure (separation) occurred. This residual strength was recorded.

IV. RESULTS AND DISCUSSIONS

A. Static Indentation Tests

Static indentation tests were conducted on 2024-T3, 7075-T6, the two ARALL materials, and on the AS6/5245 composite material. The static indentation tests were conducted for the basic 2024-T3 and 7075-T6 sheet material because the ARALL systems were made from these materials. Therefore it was of interest to compare the ARALL laminate performance to the sheet performance.

The load levels at which the first visible evidence of indentation appeared, first damage occurred, and front and backface damage occurred were noted and recorded. The load/displacement curves for the sheet aluminum alloys were quite trivial. The load/displacement curves showed the plastic deformation of the sheet, then a rapid decrease in load with increasing displacement once the sheet cracked. However the load/displacement curves for the ARALL materials and composite were more interesting.

Figure 5 is a typical load/displacement record for the ARALL materials. The back ply (ply on the side opposite of the punch) was the first to crack (see drop in curve on Figure 5.) Figure 6 shows such a back face crack that is perpendicular to the fibers. With increasing displacement the middle and front face plies subsequently cracked. All three ply failures produce discrete drops in the load-displacement curve. The energy required to produce this through the thickness damage is the shaded area under the curve as shown in Figure 5. With increasing displacement these ply cracks branched into longitudinal cracks, parallel to the aramide fibers at the edge of the indentor's contact area as shown in Figure 7. This type of splitting was not observed in the monolithic sheet material.

Figure 8 is a typical load/displacement record for the composite material. Rather early in the load/displacement record there was evidence of delamination or ply cracking. The first major damage event (as indicated by a large drop in load) was back ply cracking. This type of damage accumulation was addressed in reference [12]. Front and backface damage usually coincided with the maximum load, therefore the energy for through the thickness damage is the area under the curve as shown in Figure 8.

Figure 9 gives the static indentation loads for the material systems tested. The triangular symbols indicate the load levels at which indentation evidence was visually observed. Evidence in the ARALL material was detected at a relatively low load while evidence in the composite material was not detected until a load level higher than the load required to cause first damage. The load levels for first damage and front and backface damage in the ARALL materials and the composite were about equivalent. The load to cause damage in the sheet aluminum was much higher. The first damage and the through damage occurred at the same time for the sheet aluminum.

Figure 10 gives the static indentation test results in terms of energy. The trends in the results are similar to those noted for indentation loads. The ARALL material required more energy than the composite for first damage. The ARALL material with the 2024 aluminum laminates required significantly more energy for through the thickness damage development than did the ARALL made with 7075 aluminum. Once again, the sheet aluminum materials required much more energy for through damage development than either the ARALL materials or the composite. It appears that the unidirectional orientation of the aramide fibers may hurt the impact performance of the laminate by causing the aluminum laminates to split. The sheet 2024 aluminum absorbed more energy than the 7075 aluminum, thus explaining the ARALL material behavior.

B. Dynamic Impact and Residual Fatigue Behavior

Two levels of dynamic impact were chosen for comparing the residual fatigue strength of the ARALL and composite materials. These levels are indicated by dashed lines in Figure 10. A level of 6.8 N-m was chosen because both the ARALL and composite materials would have some permanent damage. A level of 12.4 N-m was chosen because the materials systems would have or nearly have through the thickness damage.

In all three materials, the visually observed damage that developed due to the dynamic impact was essentially the same as that developed in the static indentation tests at the same energy level.

After the dynamic impact, the specimens were fatigue tested. At both impact levels, both the prestrained 7075 aluminum ARALL and the composite survived two million load cycles with very little (no noticeable) additional damage accumulation beyond that caused by the impact. Although the 7075 ARALL had sizable cracks in the plies due to the impact, they did not grow because of the compressive residual stresses in the aluminum due to prestraining. However, the 2024 ARALL material that had not been prestrained failed at 1,332,300 cycles when impacted at 6.8 N-m and at 155,300 cycles when impacted at 12.4 N-m. The initial damage due to the impact was about the same for the 2024 and 7075 ARALL materials with perhaps the 2024 being slightly less damaged. However, since the 2024 system did not have the advantage of the prestraining, the cracks grew to failure at the cyclic stress level of 207 MPa. The cyclic stress level of 207 MPa is very high for aluminum alloys. Reliable crack growth predictions indicated that the same initial damage (crack length) due to impact would have grown to failure in approximately 550 cycles in a similar specimen made of sheet 2024-T3 aluminum. Therefore, the 2024-T3 ARALL material showed a significant improvement in fatigue performance over monolithic sheet. (The same impact level that would cause cracking in the ARALL may not cause cracking in the monolithic sheet. If the impact level were high enough to cause through cracking in both the ARALL and monolithic sheet material, the ARALL would give longer residual fatige life.)

The 7075 ARALL and the composite specimens that did not fail in fatigue were then statically pulled to failure. The composite material gave significantly higher residual strength as shown in Figure 11. The 7075 ARALL had a residual strength of 280 MPa for the 12.4 N-m impact and 450 MPa for the 6.8 N-m impact.

V. CONCLUDING REMARKS

Aramide fiber reinforced aluminum laminates (ARALL) are a promising new breed of material that represent a cross between resin matrix composites and metals. Two types of ARALL (7075 aluminum prestrained and 2024 aluminum not prestrained) were static indentation tested and the results were compared to sheet 2024-T3 and 7075-T6 aluminum alloys. A state of the art composite (AS6/5245) was also tested and compared to the ARALL. Further, the two types of ARALL material and the composite were dynamically impacted at two energy levels and fatigue tested to determine residual fatigue strength. This test program resulted in the following conclusions:

1. The ARALL material had lower impact damage resistance than monolithic sheet aluminum. The unidirectional aramide fibers seemed to degrade the energy absorbing capabilities of the laminate by causing splitting in the aluminum plies to occur parallel to the fibers.

2. The ARALL material made with 2024-T3 aluminum had better impact resistance than did the laminates made with 7075-T6 aluminum. This behavior was attributed to the monolithic sheet 2024-T3 aluminum having higher impact resistance than monolithic sheet 7075-T6 aluminum.

3. The ARALL materials were at least equal to the composite material in impact damage resistance and were better for impact detection.

4. The composite material had higher residual tension-tension fatigue strength after impact than the ARALL material.

5. The prestraining of the ARALL greatly reduced the fatigue growth of impact damage.

This comparison between ARALL systems and advanced composites offers no clear winner. Each material has significant strong points. Certainly the fact that the ARALL materials can be cut, formed, and joined using existing metals technology is a plus. The composite still offers higher residual tensile strengths and potential weight savings, although the advantages over ARALL are not as high as over monolithic sheet aluminum alloys. The material selection process must take many aspects into account and rank the materials according to those properties most important for a given application.

VI. REFERENCES

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TABLE 1 - Material Properties

	AS6/5245	ARALL	7075-T6	2024-T3
Longitudinal Modulus, GPa	68	68	72	72
Transverse Modulus, GPa	44	52	72	72
Thickness, mm	1.45	1.34	1.62	1.31

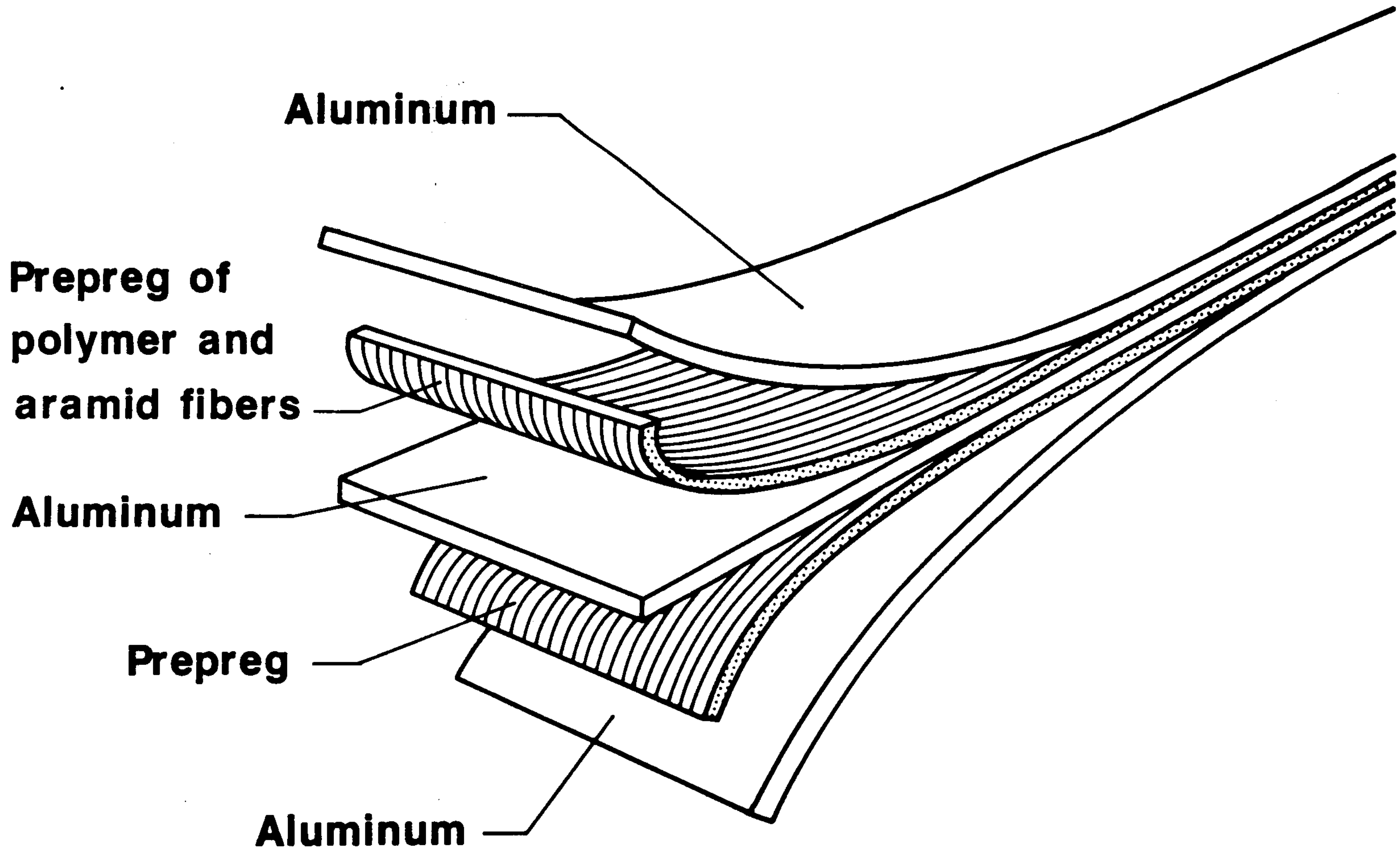

Figure 1 - Schematic of an ARALL lay-up.

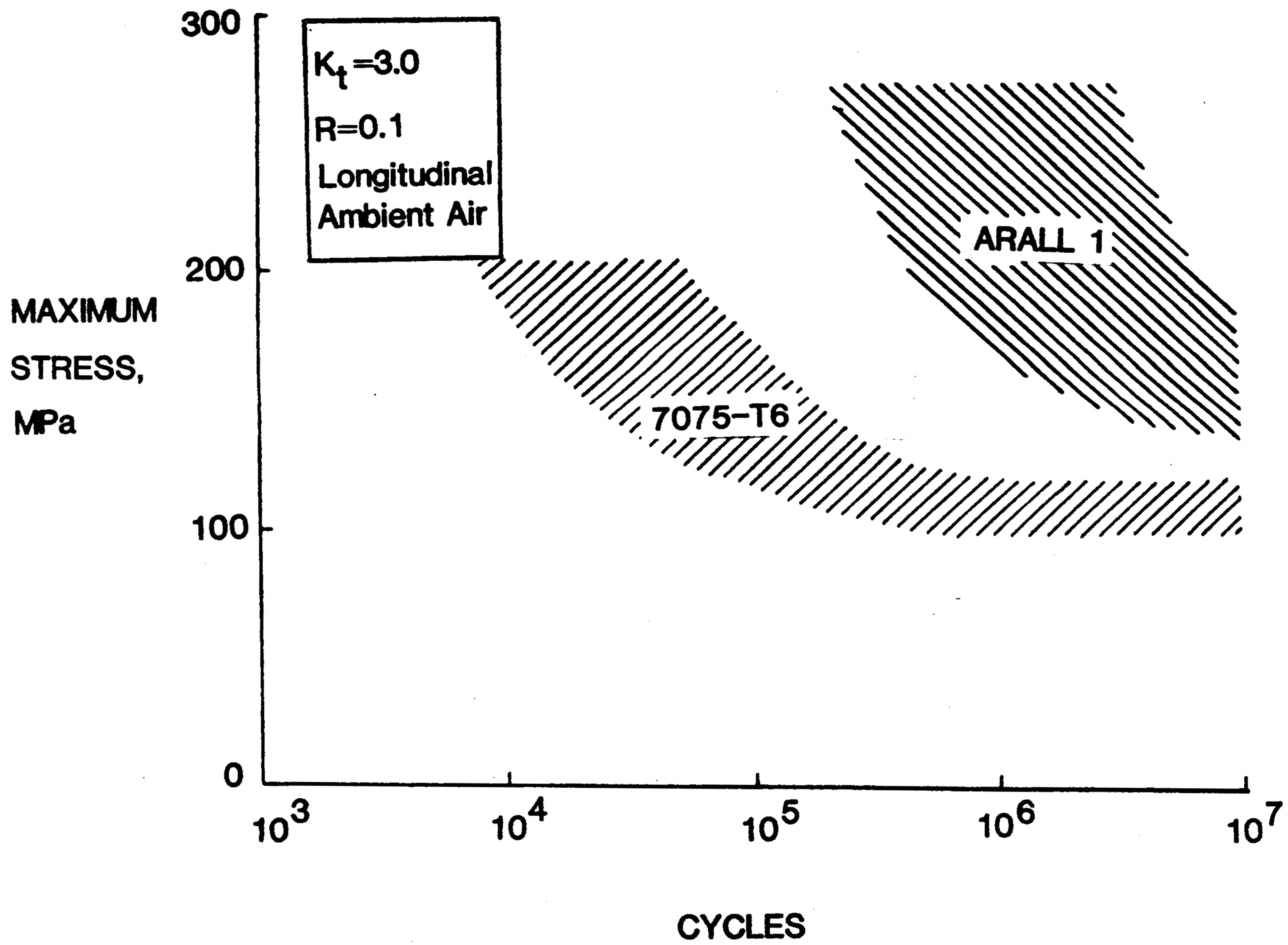

Figure 2 - S-N axial fatigue behavior of prestrained 7075-T6 ARALL material compared to sheet 7075-T6 [10].

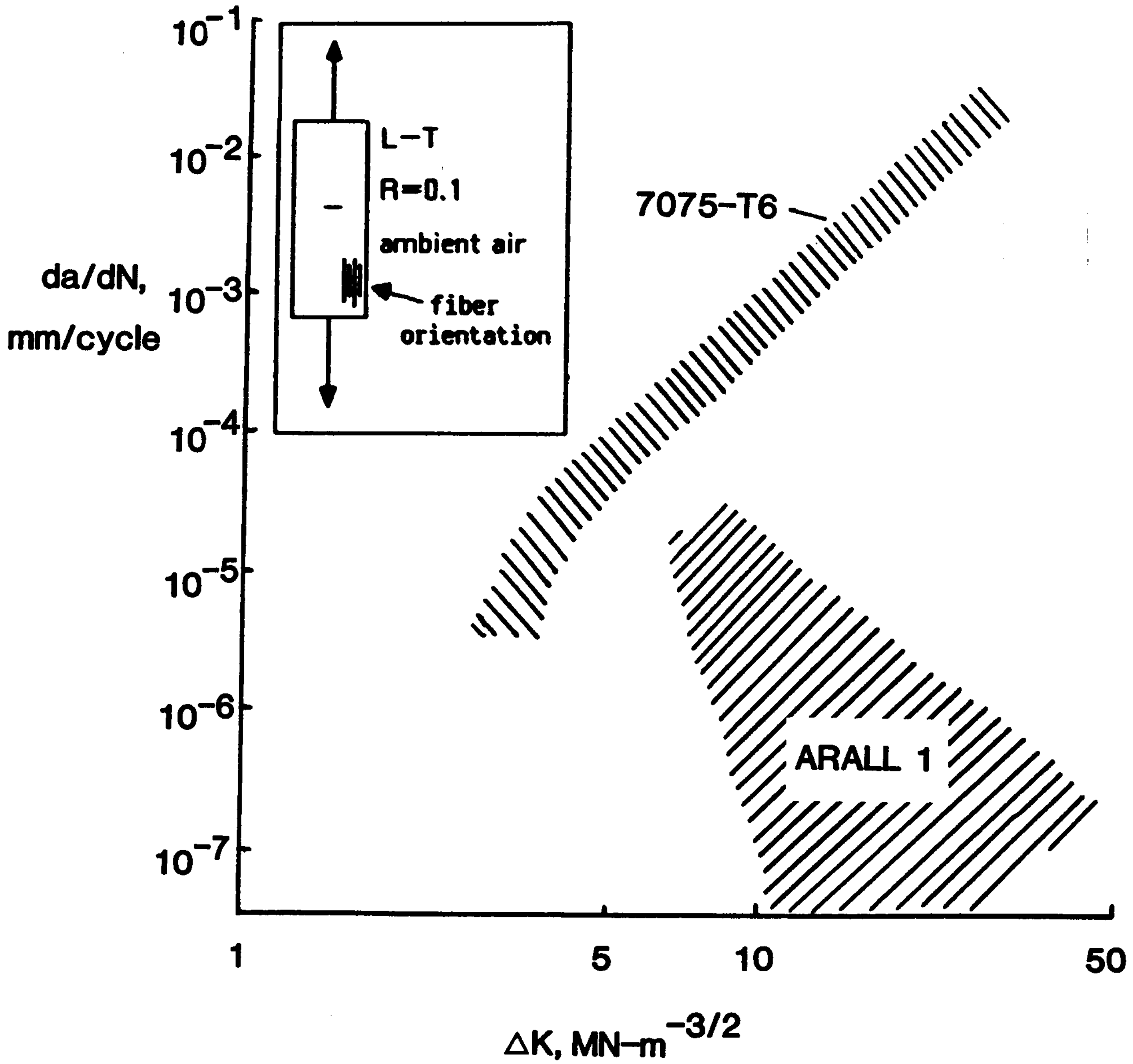

Figure 3 - da/dN vs. ΔK behavior of prestrained 7075-T6 ARALL material compared to 7075-T6 sheet [10].

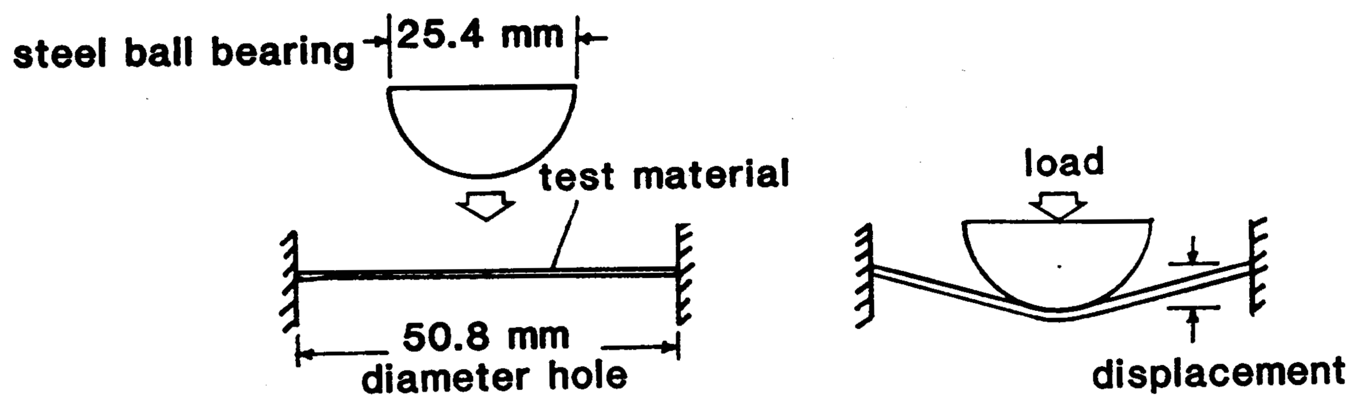

Figure 4 - Schematic of the static indentation test.

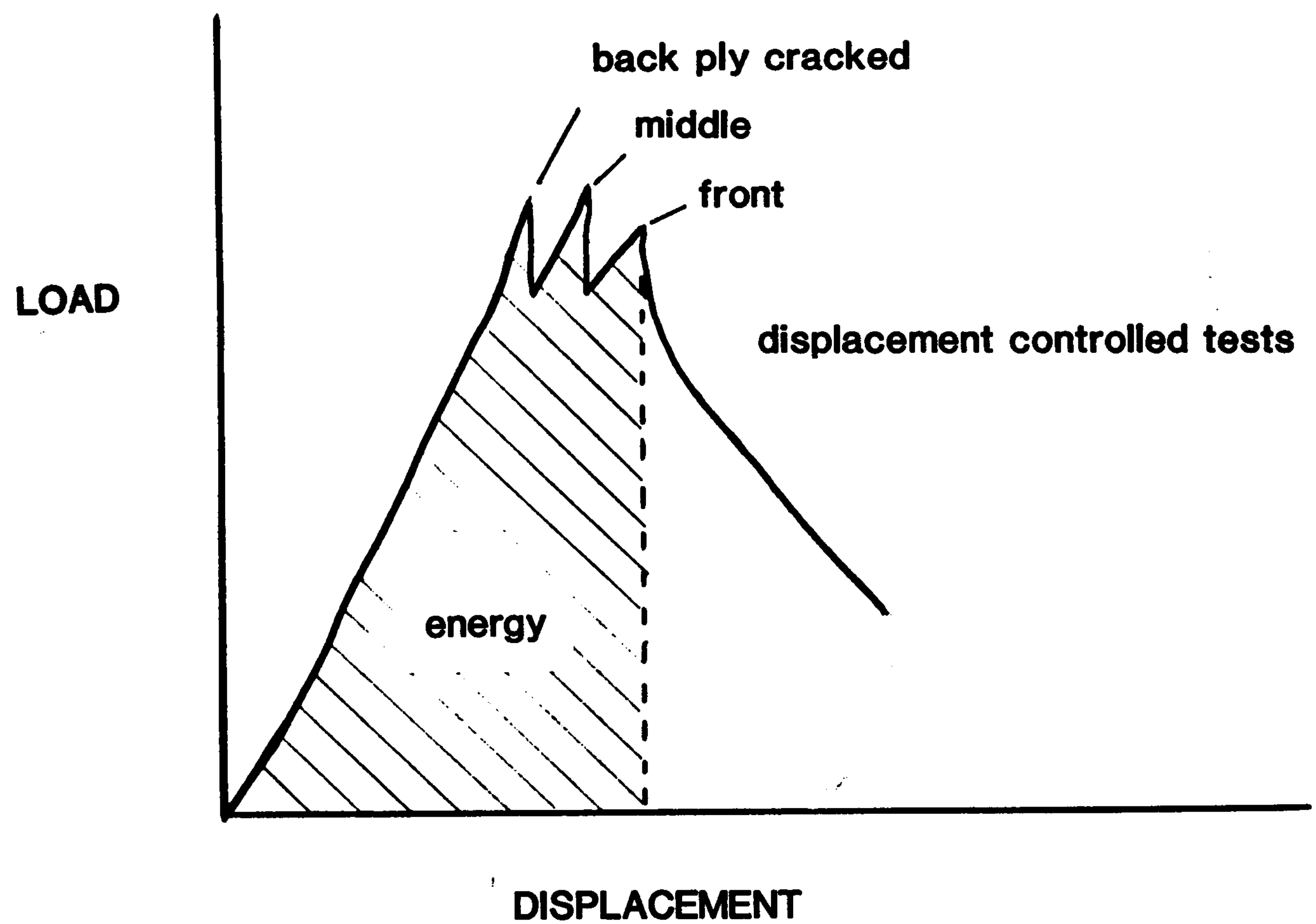

Figure 5 - Typical load/displacement plot for the ARALL material during a static indentation test.

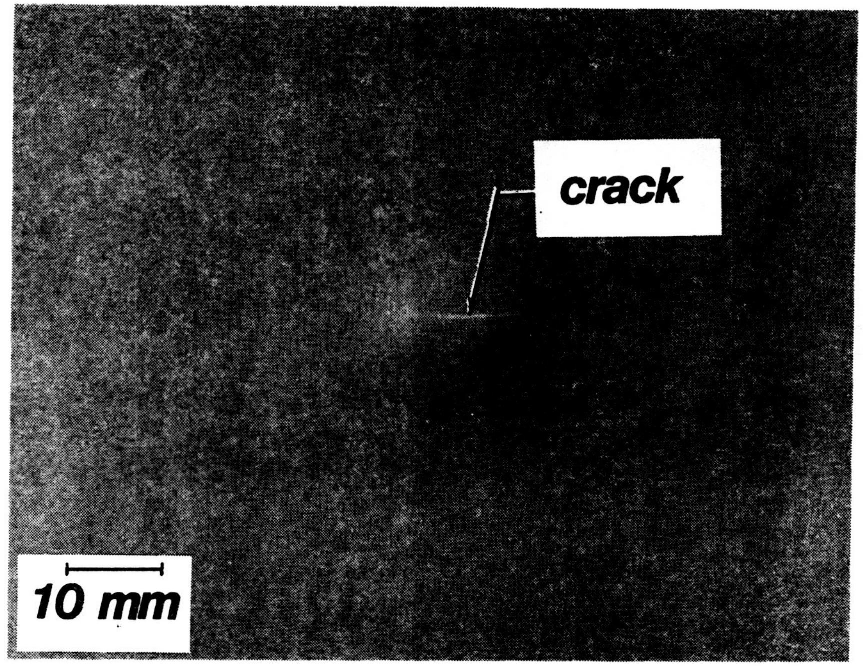

Figure 6 - Crack in the back face ply of a prestrained 7075-T6 ARALL material.

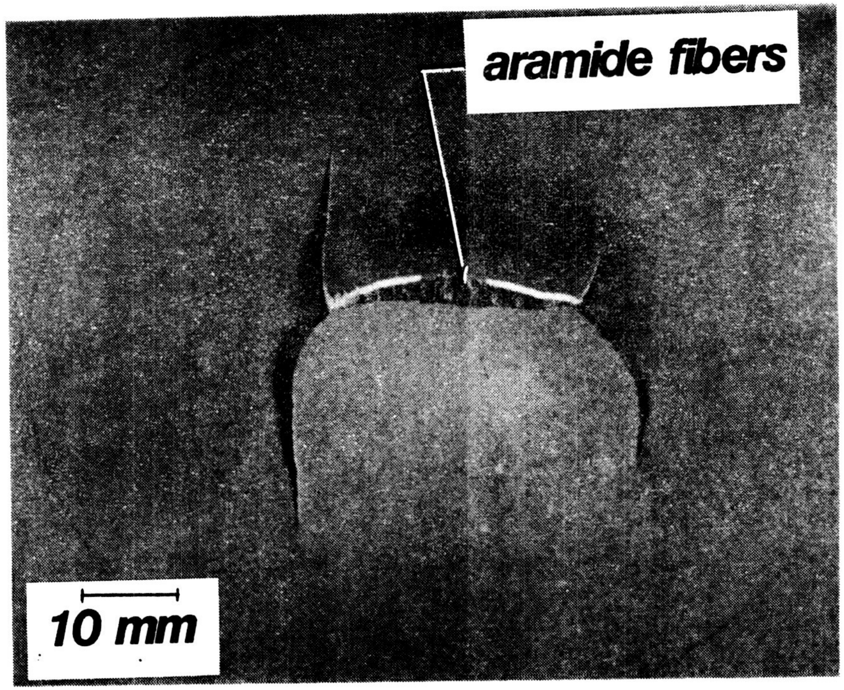

Figure 7 - Back face ply crack with branched cracks running parallel to aramide fibers.

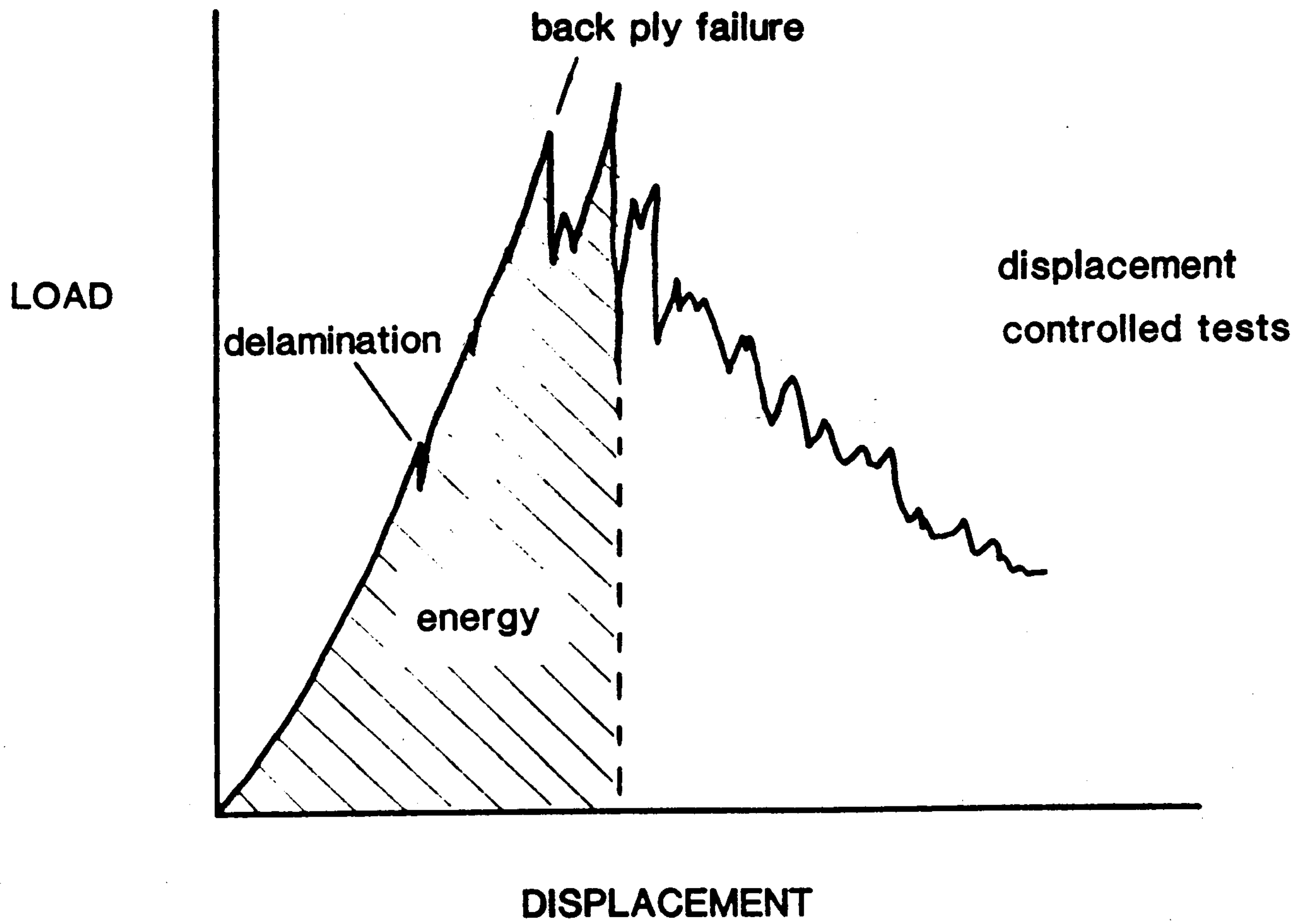

Figure 8 - Typical load/displacement plot for the AS6/5245 composite laminate during a static indentation test.

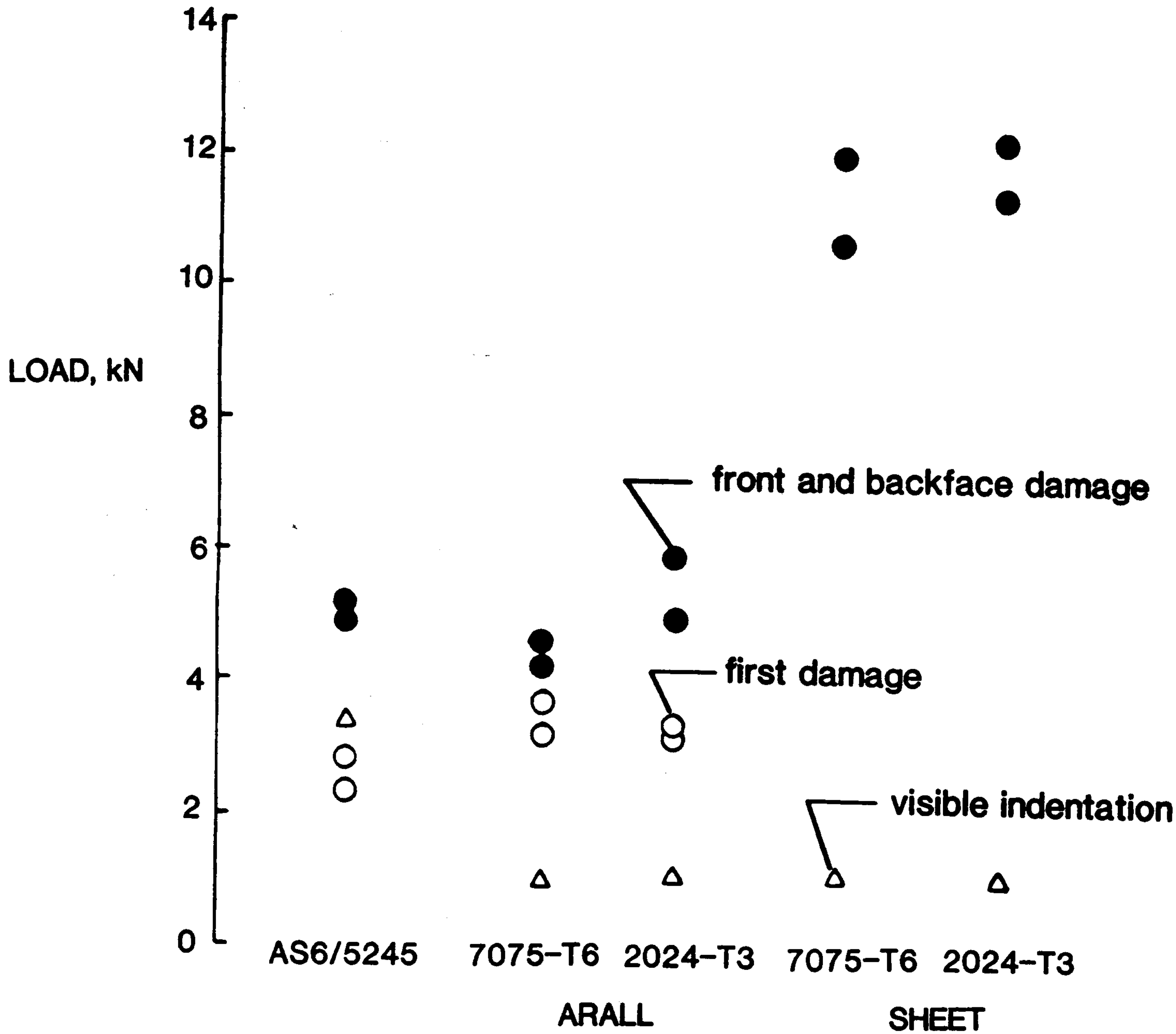

Figure 9 - Static indentation loads.

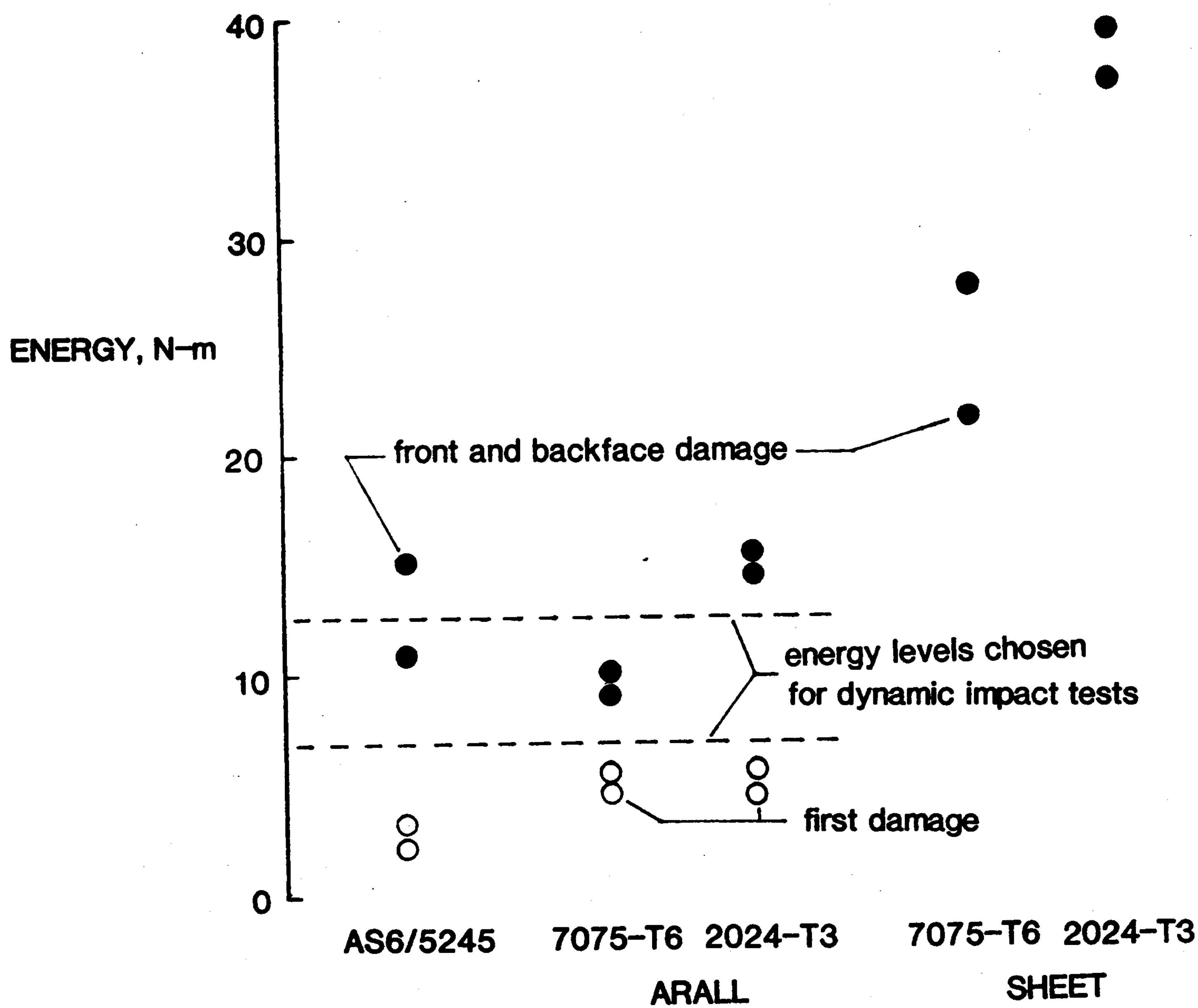

Figure 10 - Static indentation energies.

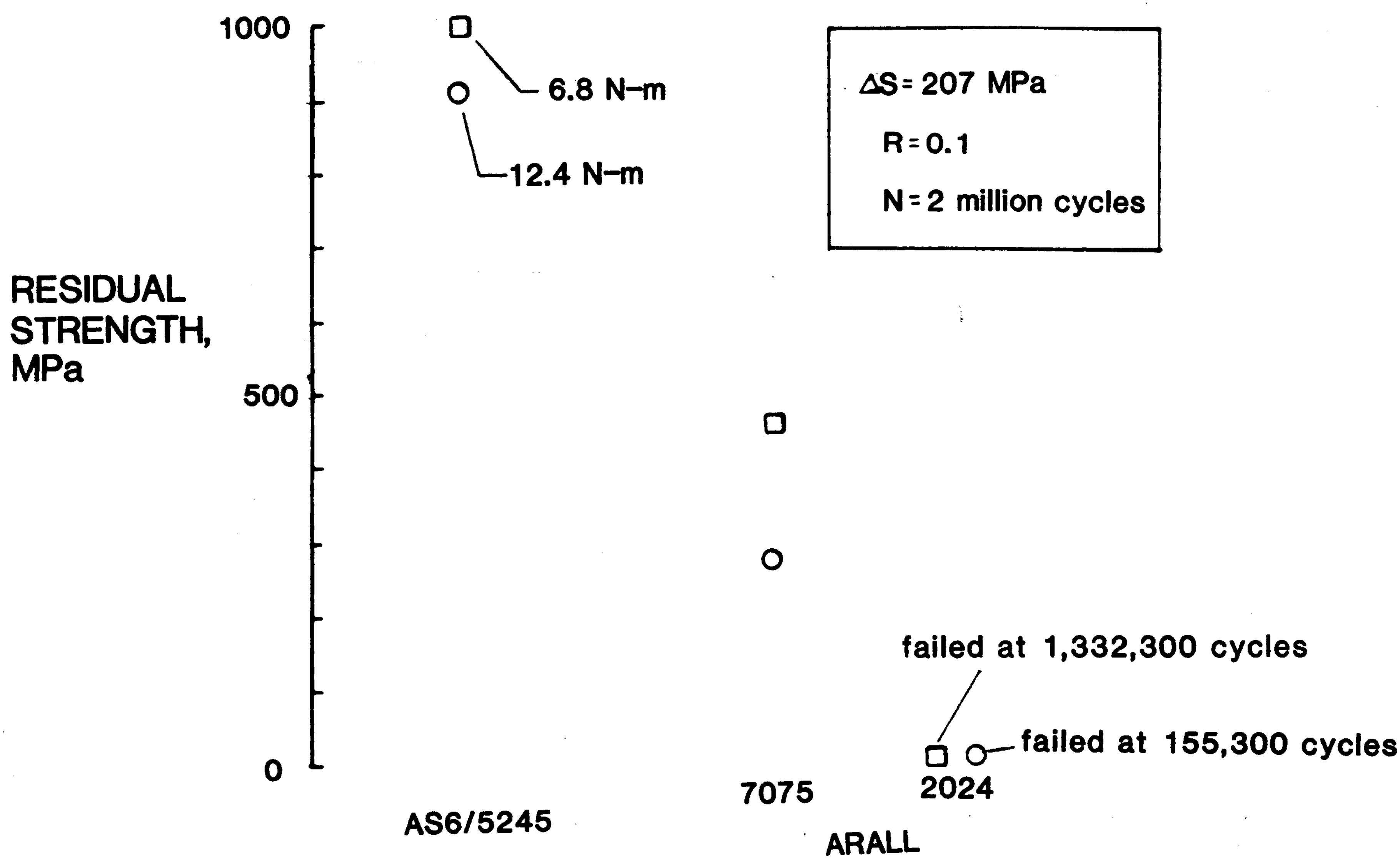

Figure 11 - Residual strength after 2 million fatigue cycles.

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16. Abstract

Aramide fiber reinforced aluminum laminates (ARALL) represent a cross between resin matrix composites and metals. The purpose of this study was to evaluate the impact sensitivity of this concept. Two types of ARALL (7075 aluminum prestrained and 2024 aluminum not prestrained) were tested through static indentation and the results were compared to sheet 2024-T3 and 7075-T6 aluminum alloys. A state-of-the-art composite (AS6/5245) was also tested and compared to the ARALL. Further, the two types of ARALL material and the composite were dynamically impacted at two energy levels and fatigue tested to determine residual fatigue strength. Both forms of the ARALL material had worse impact resistance than monolithic sheet aluminum. The ARALL material made with 2024-T3 aluminum had better impact resistance than did the laminates made with 7075-T6 aluminum. The ARALL materials are at least equal to the composite material in impact damage resistance and are better for impact detection. The composite material has higher residual fatigue strength after impact than the ARALL material and is 25 percent lighter. The prestraining of the ARALL greatly reduces the fatigue growth of impact damage.

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